ERDC/CRREL TN-05-6

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Cold Regions Data Acquisition and Analysis for Section 227 *National Shoreline Erosion Control Development and Demonstration Program* Miami Park South, Allegan County, Michigan

Michael G. Ferrick, Lawrence W. Gatto, and Christopher R. Williams

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ABSTRACT: Bank recession resulting from erosion and mass failure is a consequence of hydraulic forces and geotechnical processes. One important set of processes is soil freeze–thaw (FT) cycling and associated ground-ice growth and melt. In regions where seasonal frost forms, soil FT processes usually cause more bank recession annually than other processes. The magnitude of FT effects is variable, depending on soil type, water content, and freezing rate. The stability of the bluffs along Lake Michigan in Allegan County has been well documented with quality data, and this site was selected as a demonstration project for the National Erosion Control Development and Demonstration Program. Slope stability analyses of these bluffs indicated groundwater and soil FT effects as central to slope stability. Therefore, dewatering of the slopes is a potential means of stabilization. This technical note documents field observations, measurements, and analysis for the first year of monitoring a high bluff at Miami Park South, Allegan County, Michigan. Our data acquisition equipment, focused on freeze–thaw processes, was installed in May 2004 at a pair of adjacent bluff locations. One site was located in a section of the bluff where groundwater was removed by pumping, and the other was at a nearby control site without pumping wells. Identical instrumentation was installed at each site. The primary purposes of the field program were to evaluate: 1) the hypothesis of soil freeze–thaw as a primary cause of slope failure, 2) the effects of dewatering on soil FT processes, and 3) the timing, effects, and depth of any slope failures at either site.

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This report was prepared under the general supervision of Lawrence Gatto, Acting Chief, Environmental Sciences Branch; Lance Hansen, Acting Deputy Director; and James Wuebben, Acting Director, CRREL

The Commander of the Engineer Research and Development Center is COL James R. Rowen, EN. The Director is Dr. James R. Houston.

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MICHAEL G. FERRICK, LAWRENCE W. GATTO,
AND CHRISTOPHER R. WILLIAMS

1 INTRODUCTION

Bank recession resulting from erosion and mass failure is a consequence of hydraulic forces and soil mechanical processes. Simon et al. (1999) summarize the principal hydraulic and geotechnical processes and conditions affecting bank recession. Typical hydraulic processes include elevated river levels and velocities, wave attack at the base of shoreline banks, rill and overland runoff down the banks, and groundwater emergence at the bank face. Geotechnical processes and soil conditions interact spatially and temporally with these hydraulic processes to determine the amount of erosion and extent of failure that occurs at a specific location. One important set of geotechnical processes is soil freeze–thaw (FT) cycling and associated ground-ice growth and melt. Much previous research indicates that soil FT cycling causes 30–90% of bank failures (Thorne 1978, Sterrett 1980, Gardiner 1983, Reid 1985, Lawler 1993, Chase et al. 2001). And yet, Benoit and Voorhees (1990) and Kok and McCool (1990) report that soil FT cycling effects are among the least understood aspects of the soil-erosion process.

For areas where seasonal frost forms, Renard et al. (1997) found that processes related to bank soil FT usually cause more bank recession annually than other processes. During freezing of a soil, pore water can be drawn to the location of freezing, forming pore ice, ice lenses, or ice layers. Ice-rich, frozen soils have high mechanical strength and low susceptibility to erosion and failure. However, the formation of pore ice crystals can also disaggregate a soil, which can disrupt soil structure and decrease soil bulk density. Upon thaw, this soil is less cohesive, dense, and strong, making the soil more erodible and unstable (Gatto et al. 2001, Simon et al. 2000). Thawed soil strength often represents the annual low. In addition, the unit weight of a thawed soil is often higher than it

was initially owing to accumulation of water during freezing. This added weight further increases the susceptibility of a thawed soil to mass failure and water erosion in the spring (Gatto 2000). Consequently, spring floods often erode significantly more bank soils than floods of equal magnitude occurring later in the year after soils that have frozen and thawed regain their strength.

The variable magnitude of FT effects depends on soil type, water content, and freezing rate (Ferrick and Gatto 2005). The most frost-susceptible soils are composed of cohesive, silty sediments. Silts readily absorb water because the particles are small enough to provide comparatively high capillary rise and large enough to furnish voids of adequate size to allow quick flow of water (Jumikis 1962). These characteristics lead to rapid saturation of the voids in silty soils during freezing. Coarser-grained soils do not retain a significant volume of water after wetting, and finer-grained soils do not absorb water rapidly enough. However, Janson (1963) reported that sand may become frost-susceptible if it is well compacted, and Chamberlain[*] found that needle ice will form in almost any soil.

Chase et al. (2001) documented slope displacement along the Allegan County, Michigan, shoreline with respect to bluff lithology, atmospheric temperature, precipitation, groundwater levels, freezing of bluff surfaces, and wave activity. Slope stability analyses of the Allegan County bluffs using limit equilibrium models indicated groundwater effects as central to slope stability. Therefore, dewatering these slopes is a potential means of stabilization, but one that was untested along Lake Michigan. Because of the quality and quantity of available data, this site was selected as a prime demonstration project for the *National Erosion Control Development and Demonstration Program*. Congress authorized this Program within Section 227 (Sec. 227) of the 1996 *Water Resource and Development Act* (WRDA). The basic goals of Sec. 227 are to assess and advance the state-of-the-art of beach erosion control, to develop and demonstrate innovative methods of erosion control, and to communicate the findings to public, state and local coastal managers. The objective of the Allegan County demonstration project is to evaluate the effectiveness of active and passive dewatering strategies on slope stabilization. Glynn et al. (in prep.) provide an overview and preliminary results of the demonstration project.

[*] Personal communication with E. Chamberlain, U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory, retired, 1978.

2 OBJECTIVES

Bank soil structure, cohesion, angle of internal friction and bulk density, all varying seasonally because of frost effects, are used to derive soil erodibility coefficients in bank-erosion models. However, most models do not adjust these coefficients to account for this major seasonal variation, severely reducing model applicability in northern climes. Bank erosion and stability models must account for the effects of FT dynamics and be enhanced to include FT-induced changes to soil-mechanical conditions and relationships.

The original goal of our research was to provide the understanding of FT-induced changes to allow models such as that of Osman and Thorne (1988) to be modified for application in regions where soil FT occurs. The research plan was to use field data in concert with data collected in controlled laboratory experiments to determine the relationships among bank-failures, soil-moisture redistribution, and thaw weakening caused by soil FT cycling. Analysis of such a suite of data could provide the quantitative understanding needed to modify existing models. However, budget cuts dictated that this comprehensive plan could not be completed.

This technical note documents field observations, measurements, and data analysis for the first year of monitoring a high bluff at Allegan, Michigan, overlooking Lake Michigan. Two adjacent sites were instrumented, one in a section of the bluff where groundwater was removed by pumping, and the other at a similar site nearby without pumping wells. The primary purposes of this field program were to evaluate: 1) the hypothesis of soil freeze–thaw as a primary cause of slope failure, 2) the effects of dewatering on soil FT processes, and 3) the timing, effects, and depth of any slope failures at either site.

3 SITE DESCRIPTION

The bluff being monitored for this study of soil FT effects on bluff erosion and stability is situated along the southeastern shore of Lake Michigan near the southwestern boundary of the town of Miami Park, Allegan County, Michigan (Fig. 1). The approximate coordinates of the site are UTM 16 561343E 4701534N. The soil is classified as a Capac loam (fine-loamy, mixed, active, mesic Aquic Glossudalfs) (Knapp 1987), and the vegetation is grass and brush. This study site is 500 ft (152 m) long, and the bluff there is 80 ft (24 m) high with an average slope of 28º. Chase et al. (2001) provide a more complete description of the soil and bluff at this site.

Figure 1. Bluff at Allegan, Michigan looking north. The remediated portion of the bluff is in the right foreground adjacent to the wooden stairway. Lake Michigan is on the left.

4 INSTRUMENTATION

Western Michigan University (WMU) has monitored the bluff at Miami Park South (MPS), in association with the U.S. Army Engineer District, Detroit, as part of a long-term study of bank failure processes. Their automated instruments currently in operation at MPS to monitor the quantity of water removed, groundwater elevations and temperatures, weather, and slope response include flow meters, nested piezometers (pressure transducers), thermistors, a meteorological station, and slope inclinometers, respectively. Active (electric pumps) and passive (open holes) drains for dewatering have been installed in the sand layers along the remediated section of the bluff (Fig. 2) at depths from 10 to 35 ft (3 to 11 m). These drains connect through a series of pipes instrumented with flow meters, and discharge into sumps on the beach. The overall layout of this instrumentation is mapped in Figure 3.

Figure 2. View from below of the remediated section of bluff containing pumping wells, piezometers, and our temperature, soil moisture and resistivity instrumentation. The arrow points to our data logger and web camera.

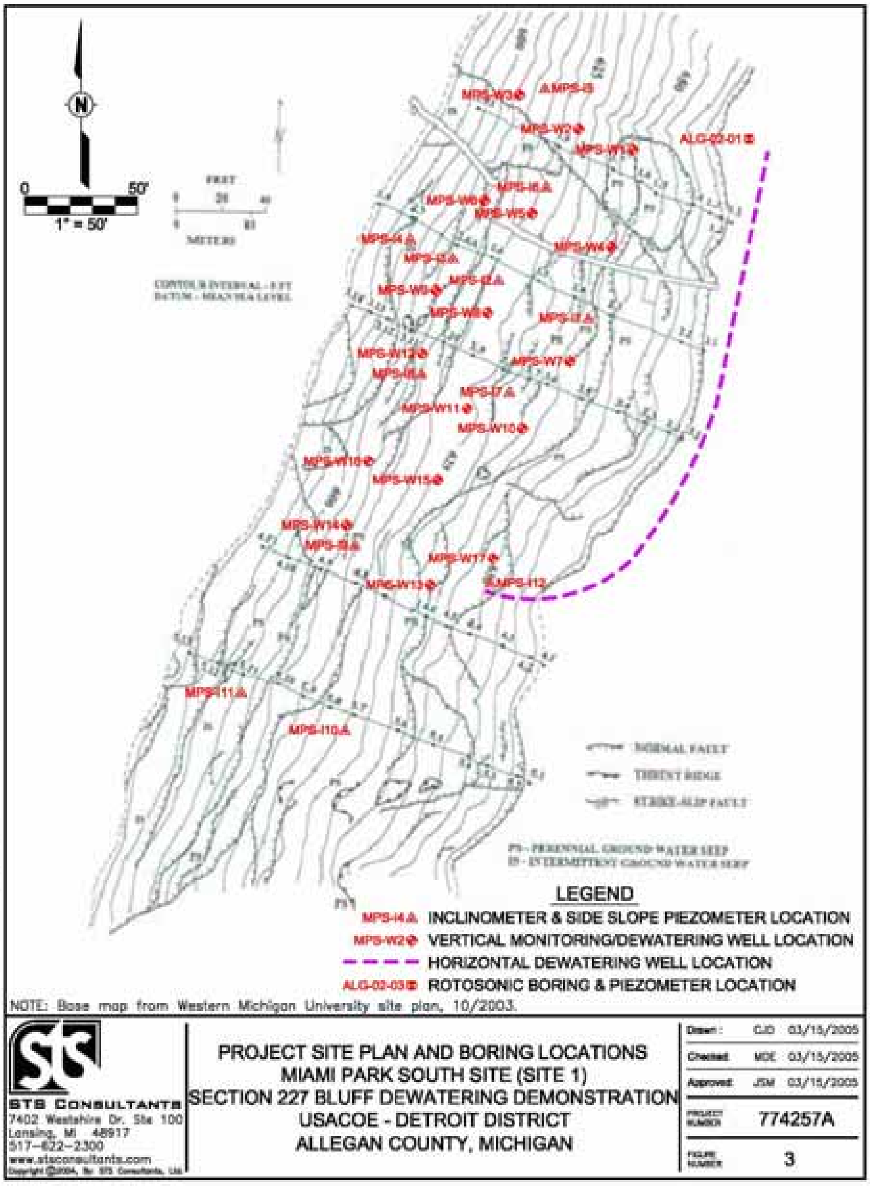


Figure 3. Site plan of Miami Park South bluff stabilization demonstration project. Remediated site instrumentation is just upslope of MPS-I7, and control site instruments are just upslope of MPS-I10.

Our supplemental data acquisition equipment, focused on freeze–thaw processes, was installed in May 2004 at a pair of nearby bluff locations at MPS. Our sites were located just upslope of MPS-I7 in the part of the bluff remediated

against slope failure by dewatering, and just upslope of MPS-I10 in a nearby control area of the bluff (Fig. 3). The instrumentation installed at the remediated and control sites was identical, and is depicted in Figures 4 and 5, respectively. Boreholes drilled at each site the previous fall allowed us to place the instruments at significant depths in the bluff. The instrumentation installed in these boreholes monitor profiles of soil moisture, temperature, and resistivity, indicating the frozen or thawed state of the bluff. Each instrument or string of instruments was hard-wired to a data logger located nearby. Web cameras at each site, mounted above the loggers, photograph ground conditions at the instrument locations three times a day to monitor snow and vegetation cover, ice formation on the slope or lake, and slumping of the slope. The data and photographs are sent from the loggers via RF radio links to the instrumentation building at the top of the bluff, and then transmitted via modem through phone lines to CRREL for web posting and archiving at https://webcam.crrel.usace.army.mil/allegan/. The loggers, powered by 12-V batteries that are recharged by 50-W solar panels, contain external backup data storage units that can be manually downloaded to preserve the data record at times when data transmission is not functioning.

Figure 4. View from above of our site in the remediated part of the bluff. Soil temperature, moisture, and resistivity instrument profiles in the bluff are marked by orange stakes, with solar panel, data logger, and web camera visible in a cluster on the right.

Figure 5. View from above of our site in a nearby control section of the bluff. Soil temperature, moisture, and resistivity instrument profiles in the bluff are marked by orange stakes, with solar panel, data logger, and web camera visible as a cluster in the foreground.

Eight specific data groups or records are taken every 4 hours at each site and stored on a Campbell Scientific CR10X data logger and associated backup data storage units (Campbell Scientific, Inc., 815 West 1800 North, Logan, Utah 84321-1784; www.campbellsci.com). The first entry in each record is the data identifier, indicating the type of data. Following the identifier are the year, Julian date, and military time that the data are obtained, and finally the data that compose the record. Soil temperatures (˚C) were measured with thermistor temperature probes constructed at CRREL with a rated accuracy of ± 0.2°C. These probes were mounted in PVC pipes and buried in the bluff so that thermistors monitored depths of 0.1, 0.25, 0.5, 0.75, 1.0, 1.5, and 2.0 m. Soil temperatures measured by the 2-m thermistor strings are recorded from shallow to deep.

Volumetric, soil-water contents (% by volume), and additional soil temperatures (˚C) were measured with Vitel Hydra–Probes (Stevens Water Monitoring Systems, Inc., 5465 SW Western Ave., Suite F, Beaverton, Oregon 97005; www.stevenswater.com). These data are obtained at five depths at each site, nominally 0.5, 1, 2.5, 3.8 and 5.4 m, and recorded from shallow to deep. The lower portion of each probe provides soil moisture and the upper portion gives soil temperature with a difference in depth of about 0.1 m between them. The soil moisture measurements use both apparent dielectric permittivity and conductivity

to obtain water content with a listed accuracy of 3% by volume. Soil conditions at both sites were saturated below 1 m when the instruments were installed. Dewatering operations should reduce remediated site soil moistures to below saturation after a sufficient period of time.

Soil resistivity (volts), listed from shallow to deep, indicates the frozen or thawed state of the soil water. These profile probes, constructed at CRREL, are composed of a series of metal rings spaced 2 in. (5 cm) apart in saturated fine-grained sand. As the freezing front in the soil progresses past a given ring, the resistivity between it and the next lower ring increases dramatically. Resistivity values near zero indicate liquid pore water, while larger values indicate increasing ice content. A total of 29 depth intervals are monitored, from the shallowest sensor pair centered at 7 cm to the deepest pair centered at 149 cm, with a resolution of 5 cm. Soil resistivity and temperature measurements are used in combination to define the depth of frost and the number and duration of soil FT cycles. These data indicate the time history of freezing of the bluff, and the effects of dewatering on the freezing. Finally, battery voltage and data logger temperature (˚C) complete each record. Logger temperature is indicative of air temperature, but with a slightly longer response time.

5 RESULTS

Active remediation by pumping to remove groundwater started 17 December 2004 and continued through 10 May 2005. Pumping rates were highly variable among the wells, but the rates at individual wells were steady through most of the period*. The total quantity of water pumped over the season from the bluff was 250,800 gal. (949 m^3), amounting to 1750 gal./day (6.624 m^3/day) or 1.22 gal./min (4.62 L/min).

Web camera photos show the condition of the ground surface, vegetation, and snow cover or surface icing development through time at the instrument location of each site. The webcam photos were not transmitted from the remediated and control sites between late September 2004 and early April 2005. As a result, the snow cover or ice conditions and associated effects on monitored parameters through the winter are not available. Air temperature data were collected at the data loggers of both sites, and also at the meteorological station located at the top of the bluff. Table 1 gives daily maximum and minimum air temperatures at all three locations for both warm and cold periods in January, February, and March 2005. This comparison indicates that these temperatures differ slightly, typically by less than 1ºC. The mean temperature difference between the control and remediated sites is 0ºC with an RMS difference of 0.4ºC. From the perspective of soil FT response, these records are interchangeable.

Table 1. Winter air temperature comparison: site 1, site 2, meteorological station.

Date	T_{max} (ºC)			Date	T_{min} (ºC)		
	Site 1	Site 2	Met Sta		Site 1	Site 2	Met Sta
1/12/05	17.5	17.4	17.4	1/17/05	–17.0	–16.5	–16.7
1/13/05	11.5	11.6	10.7	1/18/05	–18.6	–18.2	–18.0
2/5/05	12.4	12.6	11.4	1/22/05	–12.2	–11.9	–12.8
2/6/05	9.9	10.1	8.7	1/23/05	–17.9	–16.9	–18.5
2/14/05	9.8	9.8	9.6	1/26/05	–11.5	–10.9	–10.7
3/6/05	10.1	10.4	10.6	1/27/05	–19.8	–19.5	–18.4
3/7/05	8.1	8.0	10.3	1/28/05	–18.1	–17.5	–16.4

Air temperatures for the complete period of record at the remediated site are given in Figure 6. The data gap from 17 June to 13 July 2004 in this and subsequent figures was caused by a combination of data transmission malfunction and an error in the setup of the local backup data storage system. After this gap, the

* Personal communication with Dr. Ron Chase, Western Michigan University, 2005.

data storage backup was restored and worked properly for the rest of the period. Large diurnal air temperature changes are common through much of the year, but are not in evidence from mid-November through January. Short-term temperature changes during a brief period in January exceeded 30ºC, and changes nearly as large can also be noted at several other times during the year. Several brief periods with air temperatures below –10ºC occurred in mid- to late December, and again in mid- to late January. Air temperatures remained above –20ºC during all of these events. Temperatures exceeding 10ºC occurred three times in December and twice in January. Air temperatures in November through mid-December, and again in February, were generally above freezing. Even without a snow cover, these relatively mild winter temperature conditions are not usually sufficient to develop frozen ground at depth. Soil resistivity at both the control and remediated sites did not deviate significantly from 0 V at any depth during the winter, indicating that soil freezing was limited to the upper 5 cm at the measurement locations.

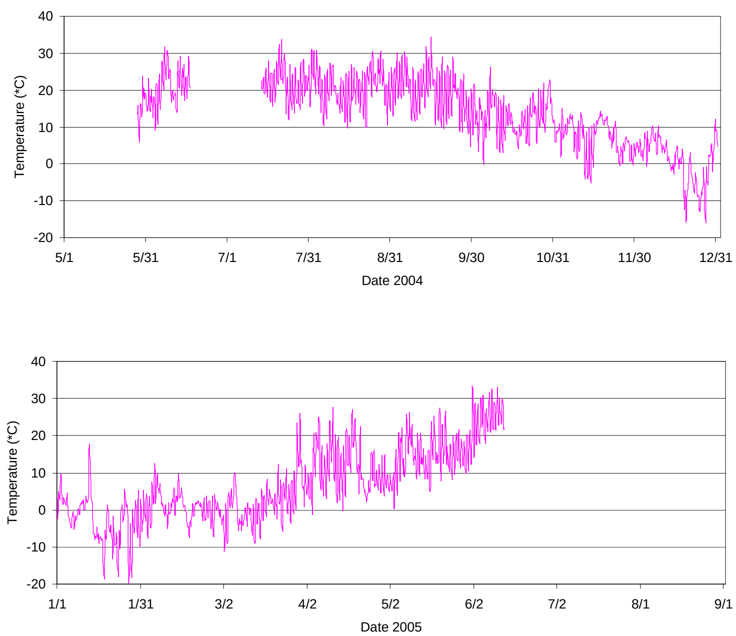
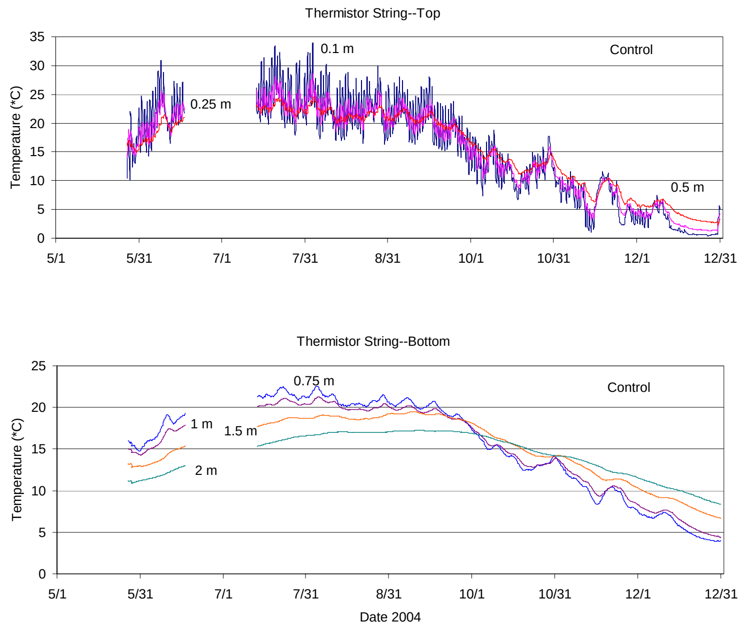
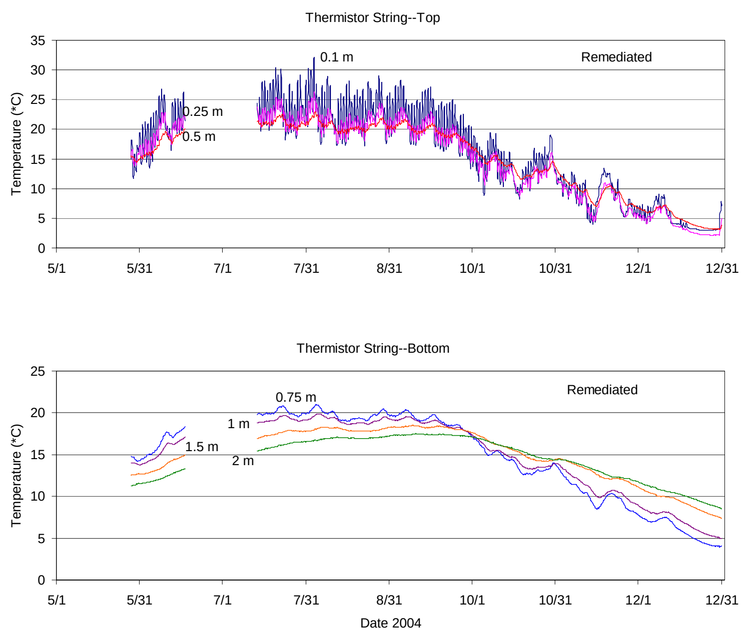


Figure 6. Logger/air temperature data from the remediated site, May 2004 into June 2005.

Soil temperature data for 2004 obtained from the thermistor strings are given in Figure 7a for the control site and in Figure 7b for the remediated site.



a. Control site.



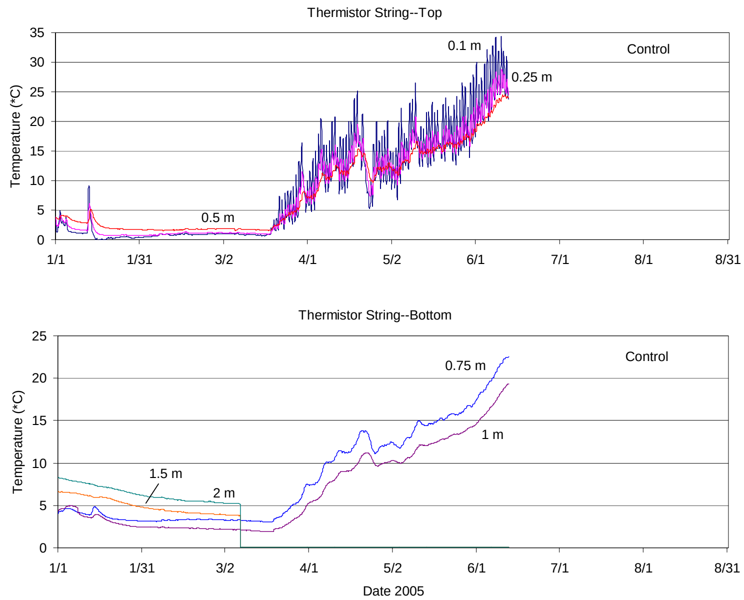
b. Remediated site.

Figure 7. Soil temperature data for the upper 2 m obtained by the thermistor string in 2004.

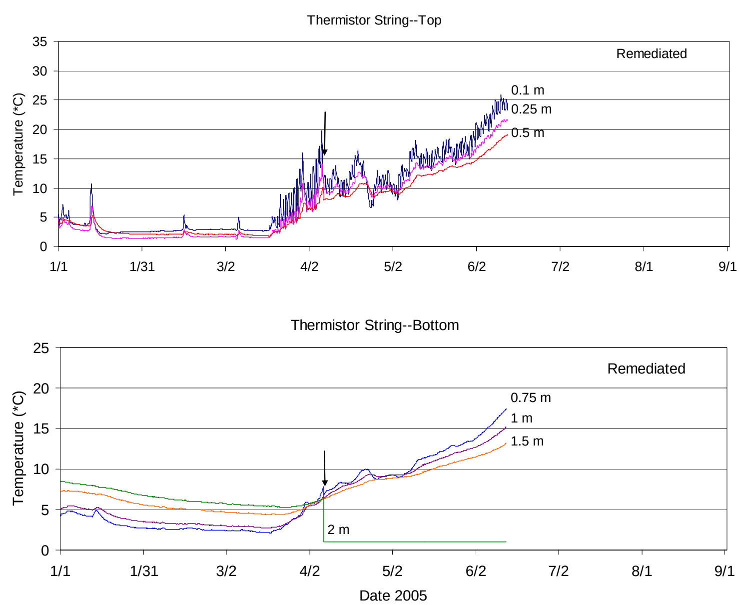
Diurnal temperature changes are clearly visible in the 0.1- and 0.25-m records at both sites, with the shallower depth producing the larger fluctuations. The temperature records at 0.5 m are smoothed, and clearly show short-term temperature trends. These short-term trends remain visible down to 1.5 m, while 2 m temperature records indicate nearly identical seasonal trends at the two sites. The 2-m temperatures were very stable through 2004, with a complete range of only 8.9ºC. The temperatures at 0.1, 0.25, and 0.5 m exceeded 30, 25, and 22ºC, respectively, at both sites during August, and are generally higher than the deeper temperatures during the summer. Soil temperatures at 0.75 and 1 m peaked near 20ºC in August at both sites, while those at 1.5 and 2 m peaked at 19 and 17ºC, respectively, in September. Shallow soil temperatures were lower during the fall than those at greater depth, with a transition that occurs in late September to early October. Minimum temperatures at the end of the year, 0.5 and 2.1ºC, were located near the top surface of each profile, while 2-m temperatures remained at 8.4ºC. These positive temperatures concur with the lack of soil freezing indicated by the resistivity and air temperature data. Several discrete warming and cooling events show that soil temperature change is initiated at the surface and propagates downward through the profile with time, lagging and diminishing in amplitude. For example, a fall temperature trough of 1.0ºC at 0.1 m on 14 November causes subsequent troughs of 6.7ºC at 0.5 m on 16 November, 9.4ºC at 1 m on 17 November, and 11.3ºC at 1.5 m on 19 November. The shallow-depth diurnal soil temperature fluctuations at both sites diminished through the fall of 2004, and disappeared in mid-December. The decrease in soil temperature fluctuations follows from diminished air temperature fluctuations.

Figures 8a and 8b extend the thermistor string soil temperature records into 2005 for the control site, and the remediated site, respectively. Starting on 31 December, the shallow ground temperatures at both sites increase and remain elevated during the first several days of January. This increase is in response to an air temperature increase immediately prior that was followed by a sustained warming. A spike in air temperature on 12 January above 17ºC is reflected in the ground temperature response at both sites down to 1 m over the next several days. Winter soil temperatures were generally stable at both sites following this event, with the exception of small increases in the upper 0.25 m at the remediated site on 15 February and 8 March. Both of these events were related to elevated air temperatures immediately before. According to the met station records for the top of the bluff, there was steady, light precipitation on 13–15 February, but no significant precipitation was recorded on or before 8 March. Also on 8 March the lower two sensors of the thermistor string at the control site were lost, probably in response to a local slope failure between 1 and 1.5 m. Progressively increasing air temperatures through the middle of March were eventually reflected in shal-

low soil temperature increases from winter levels, beginning on 20 March at both sites, and diurnal temperature fluctuations at 0.1 m resumed shortly thereafter.



a. Control site.



b. Remediated site, with arrow indicating event of 7 April.

Figure 8. Soil temperature data for the upper 2 m obtained by the thermistor string in 2005.

On 6 April the air temperature peaked at about 25ºC, and on 7 April at about midday the 2-m sensor at the remediated site was lost and all other thermistor string soil temperatures there decreased abruptly (upper part of Table 2). Temperatures at 1 and 1.5 m decreased to the pre-event temperature at 2 m (6.3ºC), while temperatures at 0.25, 0.5, and 0.75 m decreased by 1.9, 2.2, and 1.0ºC, respectively. A soil temperature decrease at this time of year indicates deeper groundwater moving into shallower depths. Following this brief excursion of a few hours, these temperatures recovered to their previous trends. There was no corresponding event at the control site, and no precipitation was recorded at the met station during this period. A probable interpretation of this event is a failure of the remediated slope between 1.5 and 2 m that caused or was associated with a short duration vertical groundwater head gradient and flow toward the soil surface at the location of the thermistor string.

Table 2. 7 April 2005 event at remediated site.

Depth (m)	*T* at 0800 (ºC)	*T* at 1200 (ºC)	*ΔT* (ºC)	Soil Mois. at 0800 (%)	Soil Mois. at 1200 (%)	*Δ* Soil Mois. (%)
0.1	11.4	10.9	–0.5			
0.25	11.9	10.0	–1.9			
0.5	10.1	7.9	–2.2			
0.75	7.8	6.8	–1.0			
1	6.7	6.3	–0.4			
1.5	6.4	6.3	–0.1			
2	6.3	—	—			
Vitel sensors						
0.5	10.4	12.5	2.1	25.7	41.1	15.4
1	7.6	9.3	1.7	41.0	38.7	–2.3
2.5	6.5	7.8	1.3	38.6	39.3	0.7
4	7.2	8.4	1.2	39.3	35	–4.3
5.3	9.4	10.6	1.2	35.2	27.7	–7.5

Figures 9 and 10 provide additional soil temperature data obtained with the Vitel probes at both sites in 2004 and 2005, respectively. Here, the depth range, 0.4 to 5.3 m, is much greater than that of the thermistor strings. The data from 2004 (Fig. 9) show higher soil temperatures at shallower depths during the warm months, a temperature inversion in the fall, and increasing temperatures with depth in the winter. Diurnal temperature fluctuations are evident at 0.5 m during the warm months, and short-term thermal events initiated at the surface can be

seen at 1 m, lagged in time from shallower depths. At depths exceeding 2 m, only seasonal temperature trends are evident. Figure 10 depicts the same winter thermal events and timing of spring temperature increase at shallow depths that were seen in the thermistor string data. Abrupt soil temperature changes occurring at the remediated site during midday on 7 April are given in the lower part of Table 2. Again, there was no corresponding event at the control site. Unlike the decreasing thermistor string temperatures, the Vitel soil temperatures all increased sharply for a few hours before returning to their original trends. These temperature increases were comparable at all depths, though somewhat larger at shallow depths. Opposite temperature trends between the thermistor string and Vitel profiles, separated horizontally by only a few meters, indicate complex, three-dimensional local flow conditions in response to the disturbance.

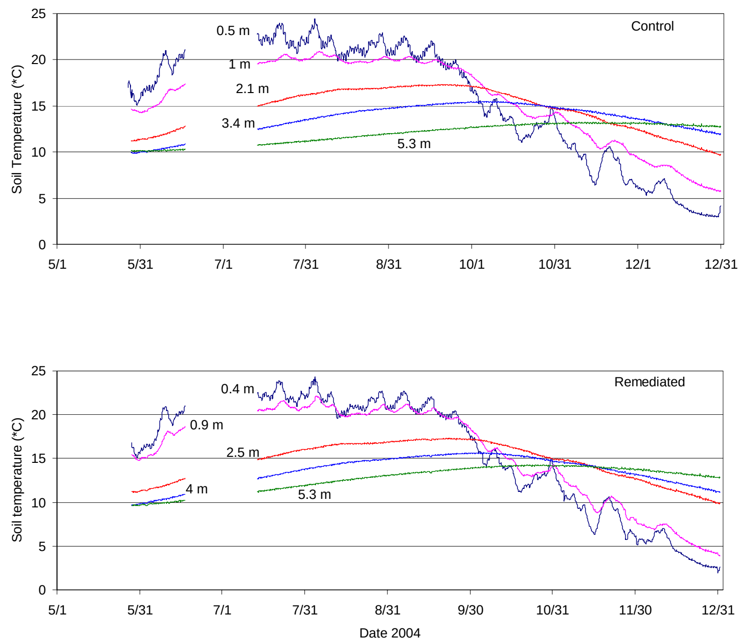


Figure 9. Shallow and deep soil temperature data obtained with the Vitel probes in 2004: control site (top), remediated site (bottom).

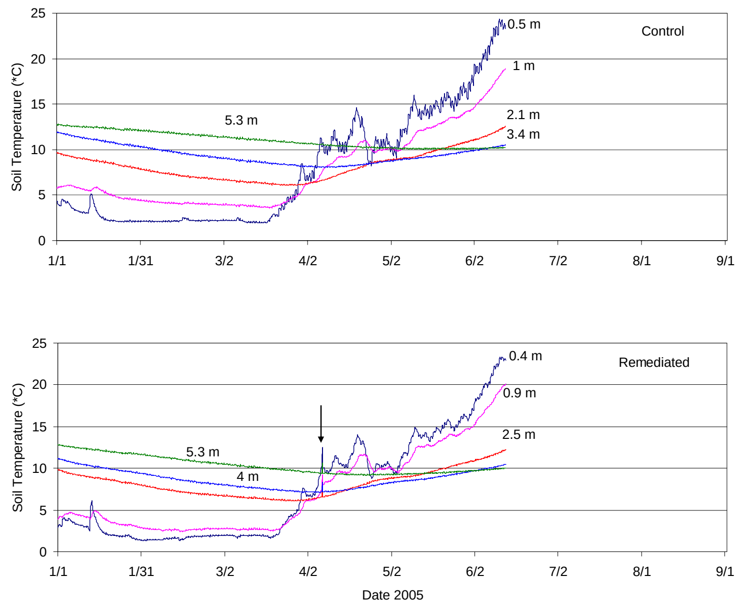


Figure 10. Shallow and deep soil temperature data obtained with the Vitel probes in 2005: control site (top), remediated site (bottom) with arrow indicating event of 7 April.

Soil moisture profiles at both sites are given in Figures 11 and 12 for 2004 and 2005, respectively. Soil moisture at 0.5 m is dynamic at both sites, especially the remediated site. Increases in soil moisture in the upper 2.2 m of the profile at both sites are frequently correlated with rainfall events recorded at the met station on the top of the bluff. Several soil moisture increases at the remediated site occur together in both the 0.5- and 1-m data. These shallow soil moisture sensors also document drying events affecting the upper portion of the soil column. In 2005 (Fig. 12), the remediated site soil moisture at 0.5 m remains dynamic, while its counterpart at the control site is much less so. On 7 April, the control soil moisture profile is undisturbed, while all remediated site sensors respond at midday (arrow in Fig. 12, bottom of Table 2). At 0.5 m the soil moisture increased significantly, while the deeper sensors at the site generally indicated diminished soil moisture, especially at 5.4 m. This deep measurement decreased by 7.5%, and then unlike any other sensor, began to fluctuate. The daily variations were initially more than 3%, but gradually diminished to less than 1% by late May. This soil moisture sensor response is consistent with dewatering of the bluff by nearby pumps. The responses of all instruments listed in Table 2 were coincident with the loss of the 2-m thermistor, linking the arrival of the piezometric surface depression at 5.4-m depth to the shallow slope failure.

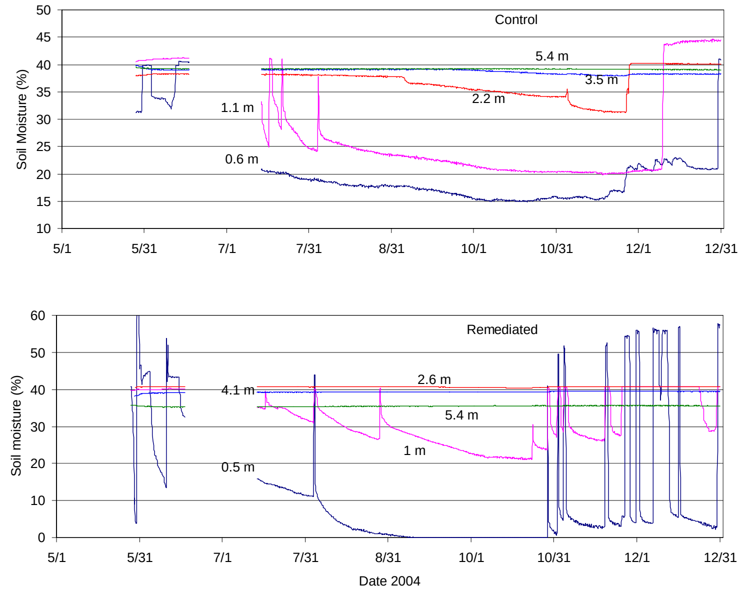


Figure 11. Shallow and deep soil moisture data obtained with the Vitel probes in 2004: control site (top), remediated site (bottom).

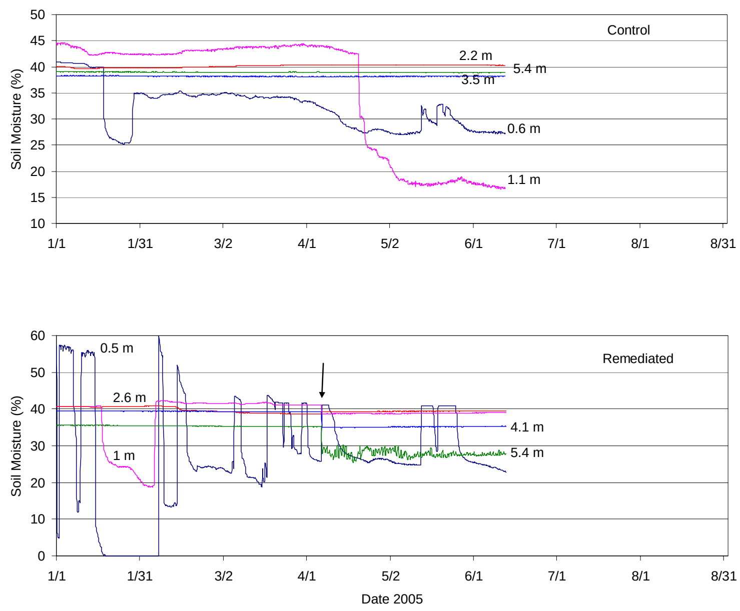


Figure 12. Shallow and deep soil moisture data obtained with the Vitel probes in 2005: control site (top), remediated site (bottom) with arrow indicating event of 7 April.

6 DISCUSSION AND CONCLUSIONS

With only one year of data, and lacking key ancillary data from the Miami Park South bluff site, it is not yet possible to develop firm conclusions concerning the mechanisms of slope failure there or the effectiveness of remediation by pumping to enhance stability. However, several insights can be obtained from data obtained in just the first year and originally designed to evaluate the relationship of freeze–thaw processes to slope failure. Overall, these data were found to be very consistent and of high quality, and provide a basis for important insights to guide future work at the site.

The winter of 2004–2005 was relatively mild at the Miami Park South site, with soil freezing limited to the upper several centimeters. This bluff contains a large quantity of water that provides sufficient heat storage to stabilize soil temperatures and resist deep freezing. Apart from the effects of pumping, all the soil moisture dynamics occurred in the upper 2 m of the soil column. Large water inputs occurred regularly at shallow depths up to 1 m. Near-surface soil moistures frequently responded to precipitation events and to extended periods without precipitation. However, these shallow soil moisture responses were often different between the two monitored sites. Soil moistures at depths greater than 2 m were high and quite stable throughout the year, but they responded abruptly when the effects of pumping reached the remediated site, especially at the 5.4-m depth.

Evidence of slope failure occurred in the spring of 2005 at both the control and remediated sites. Soil moistures near the 2-m depth where the slope failures occurred were very high at both sites and were not reduced at the remediated site by the pumping, either before or after the event. The slope failure event at the control site occurred on 8 March, weeks prior to the start of soil temperature increases in the spring. None of our nearby instrument readings were affected by this event, apart from the simultaneous loss of the 1.5- and 2-m sensors of the thermistor string. The event at the remediated site on 7 April occurred after soil temperatures in the upper 2.5 m had begun their spring increase. It had a significant effect on all the soil moisture and temperature sensors at the site, and the 2-m sensor was lost from the thermistor string. Arrival of the cone of depression in the piezometric surface attributable to the pumping abruptly reduced the 4.1- and 5.4-m soil moistures at the time of the event, with the greater reduction at the deeper depth. The subsequent fluctuating and lowered 5.4-m soil moistures indicate continued pumping effects at the site into June 2005. It is possible that the slope failure event produced a hydraulic connection between our instrument site and the pumps that did not exist earlier. However, the dryer conditions at depth

persisted into mid-June, a month beyond the period of pumping and indicative of low hydraulic conductivity near the site. The effect of pumping at the remediated site was negligible at shallower depths where the soil remained very wet and vulnerable to failure. The soil moisture at 2.6 m increased during the 7 April event and retained the increased wetness through mid-June. The coincident sensor loss and spiking of all soil moistures and temperatures implicates the pumping in this slope failure, though the mechanisms are not clear.

On the basis of this event, we speculate that pumping of groundwater may at times act to destabilize the slope at locations where soil moisture remains high at some depth in the profile. However, the reduced deep soil moistures probably reduce the chances for larger deep slope failures, and sustained pumping through a greater portion of the year would likely reduce intermediate depth soil moistures over time. Together these effects should produce the desired increase in bluff stability if water is the primary driving force. On the other hand, removal of large quantities of water via pumping will reduce the heat stored in of the bluff, promoting deeper frost penetration during colder winters and associated instability. Ferrick et al. (in prep.) reported on monitoring results over several winters at an unstable bank site in Vermont overlooking the Connecticut River. At this site soil moistures are much lower than at MPS and soil FT occurs annually, penetrating up to a meter into the soil. However, without saturated soils and excess water as a driving force, the slope failures there have been restricted to near-surface events. With less soil moisture, the soil weakening and erosion potential induced by FT are reduced (Ferrick and Gatto 2005). Our conclusion is that bluff stabilization by dewatering at MPS is promising and should continue.

There is a clear need to better understand the hydrological system that is supplying water to the bluff at MPS and its response through time. The isotopes of water, oxygen-18 and deuterium, provide natural tracers that help to identify the relationships between groundwater samples obtained at nearby locations, both to each other and to local precipitation. Isotope sampling over time, of groundwater at several locations in the study area and precipitation, would eliminate assumptions required for modeling the system by better defining the connectivity of the aquifer or aquifers, and help to explain the water sources and the effectiveness of the remediation. We recommend continued and expanded field data collection and analysis to better understand and quantify all the important processes and effects.

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14. ABSTRACT

Bank recession resulting from erosion and mass failure is a consequence of hydraulic forces and geotechnical processes. One important set of processes is soil freeze–thaw (FT) cycling and associated ground-ice growth and melt. In regions where seasonal frost forms, soil FT processes usually cause more bank recession annually than other processes. The magnitude of FT effects is variable, depending on soil type, water content, and freezing rate. The stability of the bluffs along Lake Michigan in Allegan County has been well documented with quality data, and this site was selected as a demonstration project for the National Erosion Control Development and Demonstration Program. Slope stability analyses of these bluffs indicated groundwater and soil FT effects as central to slope stability. Therefore, dewatering of the slopes is a potential means of stabilization. This technical note documents field observations, measurements, and analysis for the first year of monitoring a high bluff at Miami Park South, Allegan County, Michigan. Our data acquisition equipment, focused on freeze–thaw processes, was installed in May 2004 at a pair of adjacent bluff locations. One site was located in a section of the bluff where groundwater was removed by pumping, and the other was at a nearby control site without pumping wells. Identical instrumentation was installed at each site. The primary purposes of the field program were to evaluate: 1) the hypothesis of soil freeze–thaw as a primary cause of slope failure, 2) the effects of dewatering on soil FT processes, and 3) the timing, effects, and depth of any slope failures at either site.

15. SUBJECT TERMS

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